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RESEARCH MEMORANDUM

THE ASYMMETRIC ADJUSTABLE SUPERSONIC NOZZLE FOR WIND-TUNNEL APPLICATION

By H. Julian Allen

Ames Aeronautical Laboratory
Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
July 23, 1948

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SUMMARY

The development of an asymmetric type of adjustable supersonic nozzle suitable for application to wind tunnels is described. This new type of nozzle permits continuous adjustment of the test-section Mach number without the requirement of flexible walls. Uniformity of flow within the test section as well as the compression ratio required for the attainment of the supersonic flow are considered.

The advantages and disadvantages of this nozzle relative to the conventional interchangeable-fixed-block and flexible-wall nozzles are discussed.

INTRODUCTION

In the design of any wind tunnel, the attainment of a uniform velocity stream at the test section is of prime importance. The velocity gradients parallel and normal to the axis of the wind tunnel at the position of test must be small if reliable experimental results are to be obtained. If the wind tunnel is to be used to determine the effects of compressibility upon the flow over any model to be investigated, it is most important to attain the desired variation in Mach number by changing the velocity of the flow at the test section.

In the familiar subsonic wind tunnel, neither of these requirements is difficult to obtain. An entrance nozzle, the walls of which provide a smooth and continuous passage from the air entrance through the flat-walled test section, will suffice to prevent important gradients normal to the tunnel axis. In a nonviscous fluid, zero axial velocity gradients at the test section would obtain with parallel and flat walls at the test section, but for a real fluid

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some flair of the walls must be provided to allow for the growth of the boundary layer along the nozzle surfaces. With such a tunnel, the speed of the flow at the test section may be very conveniently varied by changing the rotational speed of the driving fan or compressor.

With the supersonic wind tunnel, the attainment of these requirements is not so simple. Only a certain family of smooth continuous wall shapes will promote the required uniformity of flow, while, even more important, the velocity at the test section can no longer be varied by changing the rotational speed of the drive compressors. This latter anomaly may be conveniently shown in the following manner: Consider the flow in the nozzle of figure 1 wherein the exit pressure P_B may be lowered with respect to the entrance pressure P_O. Since the mass flow must be the same at any position along the nozzle then, if it is assumed that flow conditions are constant across any given cross section,

$$\rho VA = \text{constant}$$

where, at any point,

ρ density

V velocity

A cross-sectional area normal to the flow direction

That is,

$$d(\rho VA) = 0$$

or the logarithmic derivative

$$\frac{d\rho}{\rho} + \frac{dV}{V} + \frac{dA}{A} = 0 \qquad (1)$$

Bernoulli's equation for compressible flow is given by

$$\frac{dp}{\rho} = -VdV$$

where p is the local pressure.

Since the square of the velocity of sound is given by

$$\frac{dp}{d\rho} = a^2$$

then

$$\frac{d\rho}{\rho} = -\frac{VdV}{a^2} = -M^2\frac{dV}{V}$$

and equation (1) becomes

$$\frac{dA}{A} = -\frac{dV}{V}(1-M^2) \tag{2}$$

If the velocity at all stations is less than sonic, then from equation (2), the familiar result that the Mach number (i.e., the velocity) increases as the area decreases is obtained. At supersonic speeds, when $1-M^2$ is seen to be negative, the reverse is true. At the speed of sound, moreover, $1-M^2$ is zero so that dA must be zero. That is, if a Mach number of unity is attained, it is only attained at the minimum area, or throat, section.

The flow behavior as the exit pressure P_s is reduced below P_o is then the following: Starting from rest, the velocity will increase and will be a maximum at the throat. This is the familiar condition with a subsonic wind tunnel, as shown by curve A of figure 1. When P_s is sufficiently below P_o to have the sonic speed attained at the throat (designated a*) as shown by curves B and C, no further reduction in P_s will increase the throat velocity and the nozzle is said to be "choked." Instead, a supersonic flow downstream of the throat will be obtained which will be abruptly terminated by a compression shock wave normal to the stream, the axial position of which will be determined by the pressure difference $P_o - P_s$ which is provided. This case is shown by curve C.

Since the flow is choked then it is clear that ahead of the normal shock wave the velocity at any station is a function only of the local area as it is related to the throat area. Thus for a supersonic wind tunnel the speed at the test section is uniquely determined by the ratio of the test-section area to the minimum or throat area ahead of it, the pressure difference $P_o - P_s$ being that required to maintain the normal shock downstream of the test section. The ratio of areas required as a function of test-section Mach number is shown for a nonviscous fluid (wherein the boundary layer need not be considered) in figure 2.

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The nozzle of figure 1 could provide any supersonic speed required for a model test if the model were moved to the appropriate position downstream of the throat. The flow, however, would be unsatisfactory because of the axial velocity gradient. Instead, a passage with a concave-walled section following a convex-walled section, such as shown in figure 3, would be required.

To obtain the required speed at the test section, the geometry of the nozzle forward of the test section must be varied (as indicated by the dotted curves) so as to obtain the proper ratio of test-section area to throat area, as well as to provide such a passage as will meet the required zero velocity gradients at the model position. This latter requirement, not so simple to attain as in the subsonic case, has been classically treated by Prandtl and Busemann employing the method of characteristics which has been thoroughly treated in numerous papers. (See, e.g., references 1 and 2.)

Clearly, it would be possible to design a series of interchangeable nozzle shapes of fixed form which would, with the proper geometry between the throat and test section, give as many different test Mach numbers as desired. This has been the scheme employed on most supersonic wind tunnels built to date. It has the advantage of simplicity but suffers from two major disadvantages: First, only as many supersonic test speeds are available as individual fixed nozzles so that if small speed increments are desired the number of nozzles required becomes large and the cost of such an installation accordingly great; and, second, for large wind tunnels the scheme becomes impractical mechanically, since the nozzle block weight becomes so great as to make the changing of the blocks too difficult and time consuming.

To avoid the difficulties of the fixed nozzles, the variable geometry nozzle was developed. With this arrangement, as it has been employed to date, two opposite walls of the nozzle are rigid, flat, and parallel, while the remaining two walls are sufficiently thin and flexible to be warped, by a system of jacks, to the required nozzle shapes. This method has the advantages that any test-section speed over the extremities of the speed range may be obtained by proper positioning of the jacks, and the change may be made without dismantling the tunnel as is required with the interchangeable nozzle system. Of course, there are numerous disadvantages to the multijack, flexible-wall nozzle. The flexible wall must be sufficiently thin as not to overstress the plates when the walls are flexed to encompass the required speed range. On the other hand, to keep the jack spacing as large as possible and so to reduce the number of jacks required, the plate must be maintained as thick as possible to prevent sagging or hogging of the plate between jacks due to local air-pressure differences across the plate as well as, in a minor degree, to the weight of the plate itself. Thus high plate stresses are occasioned, and hence one objection to this type of nozzle is that danger of overstressing of the plate (with resulting permanent set or structural failure) can easily occur by improper jack operation, necessitating elaborate safety devices to prevent such an occurrence.

The design and construction of the jack attachments to such a highly stressed plate, the elaborate system of jacks, each of which must have the absolute minimum of backlash, the complication of requiring pressure seals which will not leak and yet will allow motion of the plate, the complex control system for the jacks, and many other factors introduce mechanical complexity. The flexible nozzle of the Ames 1- by 3-foot supersonic wind tunnel shown in figure 4 attests to this fact. As a result of this complexity, high cost constitutes a major objection to the flexible-wall nozzle.

As is evident from the foregoing, neither the fixed-interchangeable nozzle system nor the flexible-wall nozzle method, as it has been used, constitutes a solution to the problem of obtaining a suitable supersonic nozzle for wind-tunnel application satisfactory in all respects.

At the Ames Aeronautical Laboratory, several unique methods for solving this problem have been developed. It is the purpose of this paper to describe one new type of nozzle that has been developed by the NACA which obviates most of the difficulties of the older types that have been previously employed.

THE ASYMMETRIC ADJUSTABLE NOZZLE

A. Silverstein of the Flight Propulsion Research Laboratory of the NACA, in an effort to circumvent the undesirable characteristics of the flexible-wall and the interchangeable fixed-block nozzles, proposed what is now termed a "plug type" nozzle. This nozzle, which is shown diagrammatically in figure 5, consists of a trumpet-shaped duct in the center of which is inserted a surface of revolution, the plug. It is clear from the figure that, if the plug is moved to the position A, the cross-sectional area decreases uniformly to the test section and hence the duct will act as a conventional nozzle suitable for velocities up to sonic at the test section. With the plug in position B, however, the area, by proper dimensioning of the duct and plug, may be made a minimum at a station on the plug forward of the test section. The test-section Mach number may then be supersonic, the actual value being dependent upon the position of the plug within the duct. Of course to satisfactorily use such a nozzle for a wind tunnel, plug and duct shapes would have to be found which would give a test-section flow free of adverse pressure gradients. Unfortunately, it is clear that a viscous wake from the plug will trail into the test section and pass the exact position that would, in the usual case, be occupied by the model. Such a wake, of course, could not be tolerated.

It was considered that boundary-layer control might be employed to remove the wake. To determine whether or not, by boundary-layer control, the wake problem could be circumvented, a two-dimensional plug-type nozzle with and without boundary-layer control was investigated experimentally. A schlieren system was used to visualize the flow and the results of the investigation are shown in figures 6(a) and (b). In figure 6(a) the plug-nozzle flow without boundary-layer control is shown. The wake is clearly seen as is also a shock-wave system originating at the trailing edge of the two-dimensional plug. It is not considered that these shock waves could be prevented by sharpening the trailing edge.

The effect upon the flow of introducing a boundary-layer suction slot is seen in figure 6(b). It is evident that, although the wake width is reduced, it is not a significant improvement. The trailing-edge shocks also persist. Moreover, the boundary-layer suction slot in reducing the boundary-layer thickness effectively alters the plug shape in such a way as to create an additional compression shock at the slot. If the plug surface were of porous material so as to allow continuous boundary-layer removal, the flow would probably be considerably improved. Nevertheless it is doubtful that a completely satisfactory nozzle for wind-tunnel application could be developed using the plug method for speed control because of the inherent disadvantage of having the plug tip directly upstream of the test position.

In an effort to realize the advantages of the plug-type nozzle and, at the same time, avoid the adverse plug wake, the author conceived of the asymmetric nozzle shown diagrammatically in figure 7.[1]

The lower wall of the two-dimensional arrangement is horizontally translatable with respect to the upper wall. With the lower wall moved forward the minimum area forward of the test section is decreased and the test-section Mach number accordingly increased, and vice versa.

[1]It is clear that this nozzle is, in essence, one-half of a two-dimensional plug-type nozzle.

No problem of a plug wake arises for this type of nozzle and, presupposing that wall shapes could be formed to give uniform flow in the test section over the whole speed range for which the nozzle would be employed, such a nozzle would be satisfactory. There remains the problem as to whether the asymmetry would promote undesirable vertical pressure gradients of serious magnitude.

To permit studies of the flow through such a nozzle, the trial nozzle shown in figure 8 was constructed. During the course of the experiments, which were conducted by Mr. Zegmund Bleviss of the Laboratory staff, numerous upper and lower curved blocks were investigated. Side-wall pressure measurements were made and schlieren pictures of the flow were taken to determine the adequacy of the nozzle configurations.

In the early stages of this investigation, the nozzle shapes were crudely determined by simply cambering symmetrical nozzles that previous experience had indicated to be satisfactory. In later nozzles, the flow was analyzed by the method of characteristics to determine what alterations of nozzle shapes would improve the flows. Typical schlieren flow photographs of some of the nozzles investigated are shown in figures 9(a), (b), and (c).

The nozzle of figure 9(a) gave nearly satisfactory flow, while that of figure 9(b) (a nozzle which was shortened to make the assembly more compact) is definitely unsatisfactory, as is evidenced by the shock waves.

For satisfactory flow, Mach lines in the test section should be straight and parallel. To demonstrate the adequacy of a nozzle, in some cases fine scribe lines were drawn in the upper surface perpendicular to the flow direction to promote such weak shock waves in the test section as to approximate Mach waves. The performance of a nozzle with scribe marks is shown in figure 9(c). The flow, as predicted by the Mach lines, is seen to be satisfactory.

Some further alterations were made to the nozzles to improve the Mach number range over which satisfactory flow could be obtained. It was particularly desirable to be able to operate, with satisfactory supersonic flow, as close to Mach number unity as possible. After some further revisions, a minimum supersonic Mach number somewhat less than 1.1 was attained. The maximum Mach number for satisfactory flow was 2.0. Although somewhat higher speeds could be attained, separation of the flow was prone to occur on the lower wall in the test section.

The separation of flow which occurs on the lower surface is felt to arise in the following manner: In the cambered sections of the nozzle upstream of the test section, the pressure at any station must be lower at the convex wall than at the concave wall in order that the flow may be turned along the curved flow path. In the main body of the stream, the fluid is not influenced importantly by the viscosity and for this fluid the centrifugal force on each element following the curved path is exactly balanced by the pressure gradient across the nozzle. The flow in the main body of the stream is thus not influenced by the fact that camber exists. The air in the boundary layer moves at a lower velocity so that the centrifugal force on each element is insufficient to balance the pressure gradient. Hence, the air within the boundary layer on the side walls will move around the passage walls toward the convex surface. The integrated influence of the curvature is therefore to collect a much thicker boundary layer at the downstream stations on the convex plate than on the concave surface. This thicker layer is, of course, more prone to separation under the adverse pressures occurring in the diffuser.

It was apparent from pressure surveys along the walls of the nozzle that vertical pressure gradients occurred in the test section at the higher speeds. However, the indications were that these adverse gradients would not be too serious up to a Mach number close to 2.0.

The investigation of the nozzle was extended to determine the compression ratio required to maintain supersonic flow through the test section. To simulate as closely as possible a nozzle suitable for wind-tunnel application, the nozzle was constructed to permit the presence of a model support gear, shown in figure 10, immediately downstream of the test section. In order that at Mach numbers close to unity such a support gear would not choke the flow at the position of the support, the side and top walls were flared to keep the cross-sectional area at the position of the support gear greater than that at the test section. This, of course, incurred a rather rapid divergence of the flared walls in this section of the diffuser. The diffuser following the support gear was of the familiar subsonic type with a 3° half angle of diffusion at each wall as a maximum.

The compression ratios required to maintain supersonic flow were determined with and without the simulated model-support gear installed and are shown in figure 11. The presence of the support gear improves the performance as would be expected because of the flared walls opposite the position taken by the support gear. The improvement due to the presence of the support gear is probably also due, in part, to the supersonic diffusion caused by the oblique shock system promoted by the strut support.

The fact that the required compression ratios at the higher Mach numbers is greater for the asymmetric nozzle than for the symmetric nozzles considered by Crocco (reference 3) is probably partly attributable to the adverse effect of the unusually thick boundary layer on the convex wall of the diffuser. Another factor which probably contributes to this characteristic is the flared section to permit low supersonic speed operation with the support strut in place. Tests of a symmetric nozzle with similar compensation for the support strut has shown lowered efficiency at high Mach numbers like that for this asymmetric type.

The results obtained from the tests of the 1-1/2- by 1-1/2-inch model nozzle demonstrated that one of this type would perform sufficiently satisfactorily for application to a large wind tunnel, and it was decided to employ such a nozzle in the Ames 6- by 6-foot supersonic wind tunnel which was to be constructed. It was deemed advisable, however, to further investigate the nozzle as a model of the proposed one for the 6- by 6-foot wind tunnel using the largest supply of dry air at high pressures available at the laboratory. Accordingly, an 8- by 8-inch wind tunnel employing the asymmetric adjustable nozzle was constructed. This wind tunnel is shown in figure 12 with the side plates removed to show the nozzle shape. Ordinates for the lower and upper nozzle blocks are given in tables I and II, respectively.[2]

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[2]As regards the continuity of the curves between ordinates, fairness has been determined at Ames Aeronautical Laboratory using a simple curvature gage consisting of two fixed posts with a third movable post located midway between the others. The movable post is directly connected to a dial gage to read the deflection of the movable relative to the fixed posts. For the gages that have been used in the 1- by 3-foot and 6- by 6-foot tunnels at the laboratory, the fixed posts have been separated one-thirty-sixth of the test-section height. For such a gage, experience has indicated that the permissible deviation of the curvature from the local mean as measured by the deflection of the moving leg with reference to the fixed legs is 0.0005 of the distance between the fixed legs. For the 8- by 8-inch wind tunnel, the curvature variation was investigated using a gage with fixed posts 1 inch apart. The survey showed this nozzle somewhat below standard in that, in at least one instance, a deviation from the mean of 0.0008 inch was measured.

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Whereas with the 1-1/2- by 1-1/2-inch model nozzle the movable block was changed in position manually and bolted down for each setting, the moving element of the 8- by 8-inch nozzle was actuated by a lead screw from outside the nozzle. Leakage through the gap between the moving block and the side walls of the 8- by 8-inch tunnel was prevented by an inflatable buna rubber seal located in the edges of the moving element which bore against the fixed walls.

Static pressure surveys were made using orifices located in the walls of the tunnel. Typical distributions of Mach number from the beginning to end of the test section at both subsonic and supersonic speeds are shown in figure 13. It is seen that over the full test-section length, which is nearly equal to the test-section depth, deviation of Mach number along the axis is in one case ($M \cong 1.1$) as large as ±2 percent. For a model small enough to be investigated without wall interference at Mach numbers near the minimum of 1.1, the model length will be of the order of half the test-section height for which the Mach number variation along the model can be kept to about ±0.5 percent.

Surveys were also made to determine the vertical gradients in the test section from subsonic to supersonic speeds. Results of a typical survey are shown in figure 14 (for the same block positions as in fig. 13) for the vertical distribution of Mach number at a station near the center of the test section. The vertical gradients are generally satisfactory although a gradient is present at Mach numbers near 1.2 and, as noted previously for the 1-1/2- by 1-1/2-inch nozzle, at Mach numbers near 2.0.

CONCLUDING REMARKS

The asymmetric adjustable nozzle possesses several marked advantages over the interchangeable fixed-block nozzle and the flexible-wall nozzle.

Compared with the fixed-block nozzle it is clear that the major advantage of the asymmetric nozzle is that any Mach number (throughout the attainable Mach number range) can be obtained by translation of the movable block; whereas with the fixed plates, only as many Mach numbers as there are fixed nozzles are available. Again, for the fixed-block nozzle provided with blocks to give more than two or three operating Mach numbers, the high cost of the machined blocks will more than offset the cost of the movable block drive and the sealing gear in the asymmetric type. Finally, for large wind tunnels, the interchanging of blocks requires unwieldy and expensive block-changing gear as well as an unnecessarily long time to make the required changes. [redacted]

Compared with the flexible-wall nozzle it is evident that because of the relative mechanical simplicity of the asymmetric nozzle the cost of such a nozzle will be considerably lower. A second disadvantage of the flexible-wall nozzle lies in the fact that scalloping of the flexible plates can occur between jack-support points. A third advantage of the asymmetric type is that there is little possibility of structural damage to the nozzle. As noted previously, structural damage can easily occur in flexible nozzles due to improper operation of the jacks although by proper design this danger can be alleviated to a large extent. Finally, with most of the flexible-wall nozzles constructed to date there exists the possibility of excessive lost motion in the jacking gear due to required clearance and, after considerable use, to wear. Hence there is an ever present possibility that the plates will not repeatedly flex to the proper setting and so, at the very least, that the calibration of the nozzle will not remain constant.

Of course there are several disadvantages of the asymmetric adjustable nozzle in comparison with the other two types. Of most importance is the fact that the curvature of the convex and concave surfaces must be correct for all speeds of the operating range so that compared to the interchangeable block nozzle it necessitates much more careful design, and compared to the flexible-wall type it cannot be conveniently altered after its construction is completed. Certainly it is true that the asymmetric nozzles so far investigated have shown at some operating speeds undesirable horizontal and vertical gradients. The presence of the latter are particularly undesirable since they imply stream angularity. However, it is considered that these adverse gradients can be reduced to an unimportant scale by more refinement of the nozzle shape. The second major disadvantage of the asymmetric nozzles so far studied is that the Mach number range for efficient use is limited since, as noted previously, the compression ratios required at the higher speeds exceeds that for the conventional symmetric nozzles. It does not follow that such a characteristic is necessarily inherent in the type however. It has been suggested that this characteristic may result in part from (a) the effect of the flared diffuser at the position of the model support, and (b) the effect of the asymmetry in thickening the boundary layer of the convex plate. If the adverse characteristic results from the excessive flare of the diffuser, it could easily be remedied by employing inserts to reduce the diffusion angle at high Mach numbers. If the adverse characteristic results from the latter, the seal in the gap between the movable block and the side wall could be removed and the boundary layer drawn off, by a suitable pump, so as to prevent the growth of the excessively thick boundary layer on the test-section floor.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

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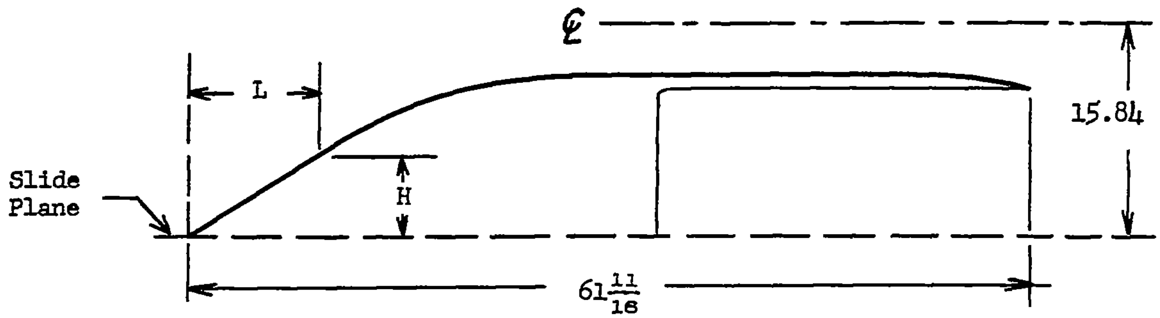
2. Puckett, A. E.: Supersonic Nozzle Design. Jour. Applied Mech. Dec., 1946, vol. 13, no. 4, pp. A265–A270.

3. Crocco, Luigi: Gallerie Aerodinache Per Alte Velocita, L'Aerotecnica. vol. XV, no. 7–8, 1935.

TABLE I.– ORDINATES OF MOVABLE LOWER BLOCK
OF 8– BY 8–INCH WIND–TUNNEL NOZZLE



Dimensions in inches

L	H	L	H
0	0	29.505	11.974
17.200	9.184	30.735	11.997
18.430	9.819	53.000	11.849
19.660	10.360	54.000	11.835
20.892	10.819	55.000	11.810
22.122	11.183	56.000	11.770
23.353	11.444	57.000	11.714
24.583	11.640	58.000	11.640
25.814	11.782	59.000	11.547
27.044	11.881	60.000	11.420
28.274	11.936	61.000	11.259

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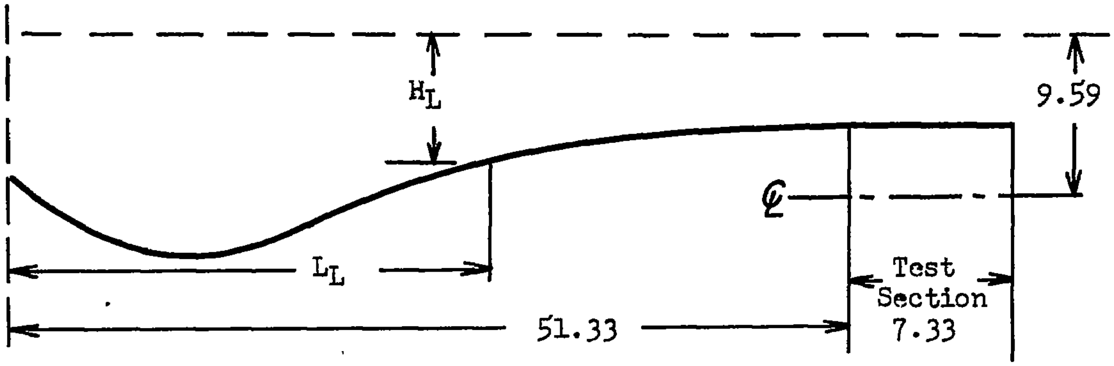
TABLE II.– ORDINATES OF FIXED UPPER BLOCK IN 8- BY 8-INCH WIND-TUNNEL NOZZLE



Dimensions in inches

L_L	H_L	L_L	H_L
0.000	10.250	26.408	10.082
1.000	10.580	27.638	9.585
2.000	10.900	28.868	9.122
3.000	11.220	30.099	8.694
4.000	11.500	31.329	8.310
5.000	11.800	32.559	7.970
6.000	12.070	33.790	7.665
7.000	12.333	35.020	7.380
8.000	12.560	36.250	7.124
9.000	12.770	37.481	6.893
10.000	12.975	38.711	6.676
11.000	13.150	39.943	6.484
12.000	13.315	41.173	6.317
13.000	13.445	42.404	6.170
14.000	13.540	43.634	6.036
15.333	13.586	44.864	5.923
16.563	13.548	46.095	5.824
17.794	13.385	47.325	5.736
19.024	13.104	48.555	5.667
20.254	12.740	49.786	5.623
21.485	12.283	51.016	5.591
22.715	11.741	51.330	5.585
23.947	11.170	54.990	5.561
25.177	10.808	58.560	5.536

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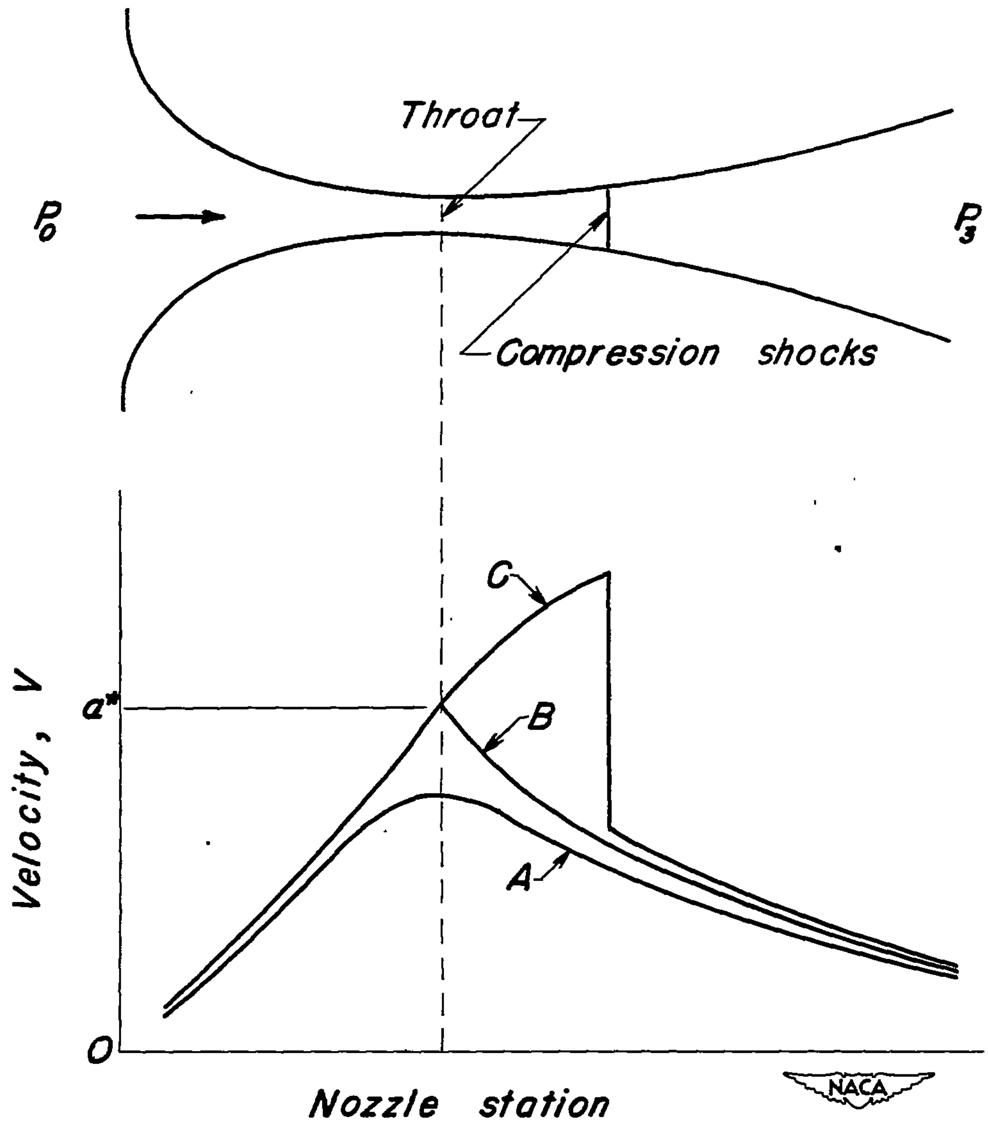

Figure 1.— Compressible flow through a convergent-divergent nozzle.

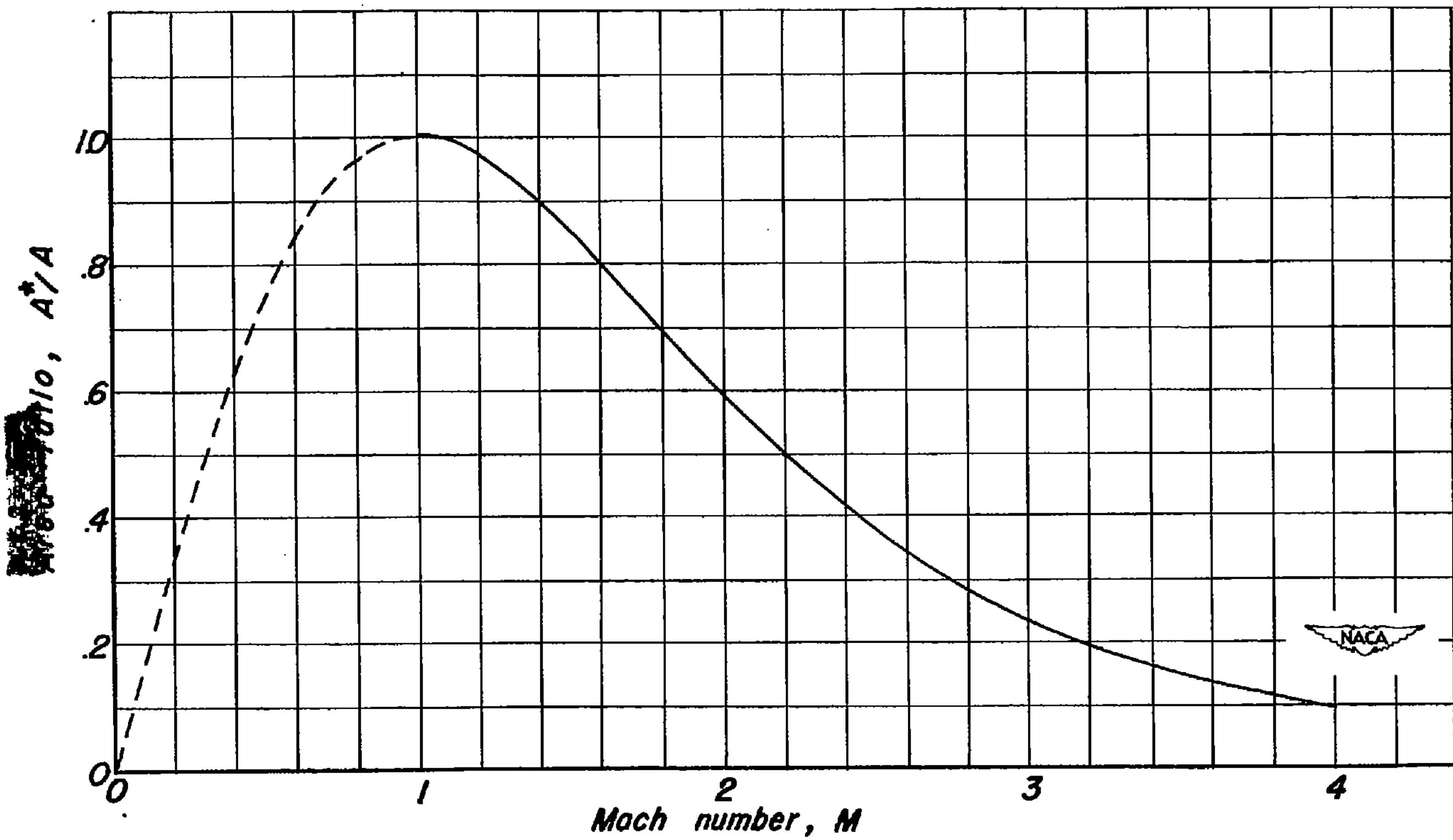

Figure 2.- Ratio of throat to test-section area for supersonic wind-tunnel nozzles.

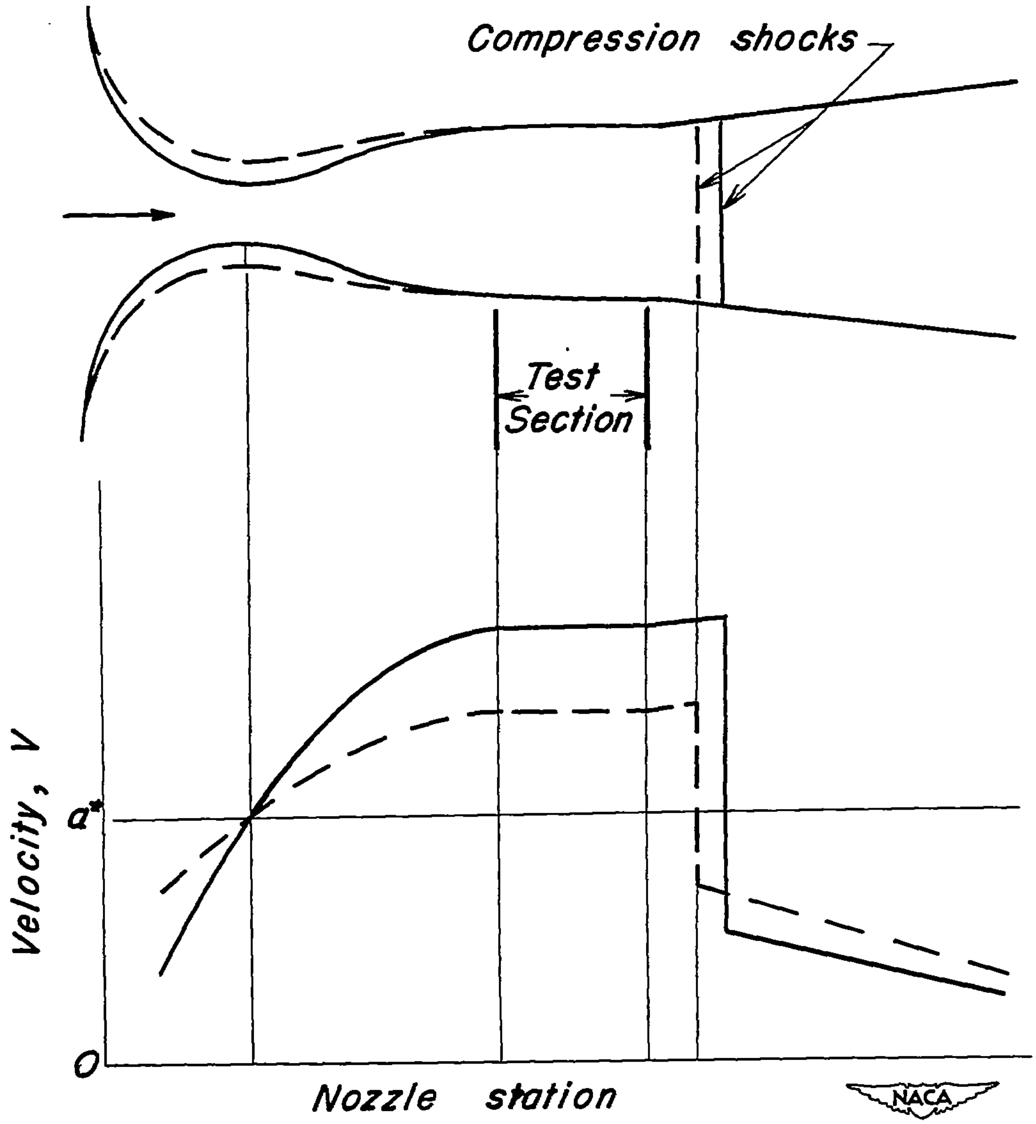

Figure 3.– Diagram of velocity through a typical supersonic wind–tunnel nozzle.

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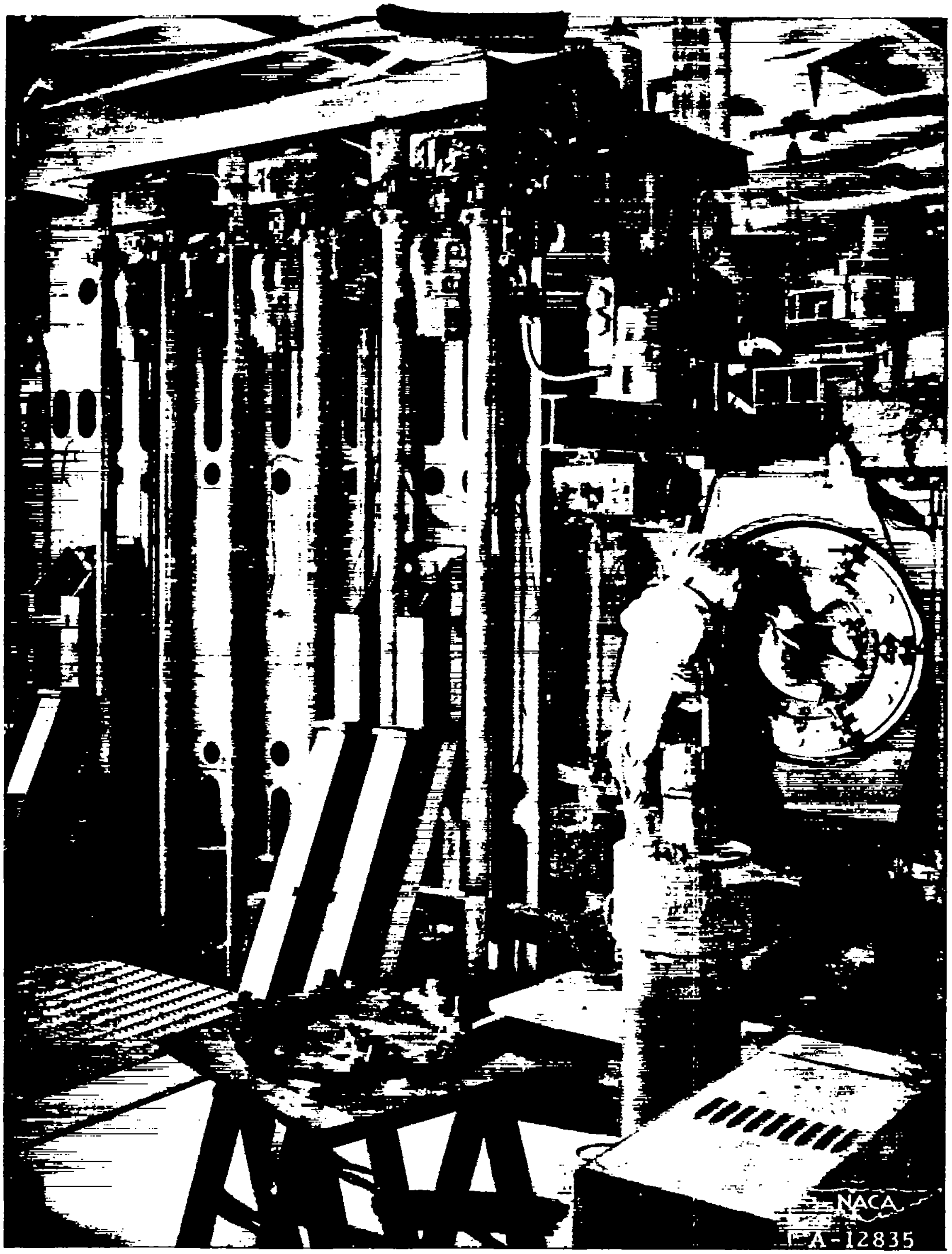

Figure 4.— One of the 1- by 3-foot wind tunnel flexible-wall nozzles of the Ames Aeronautical Laboratory.

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[redacted]

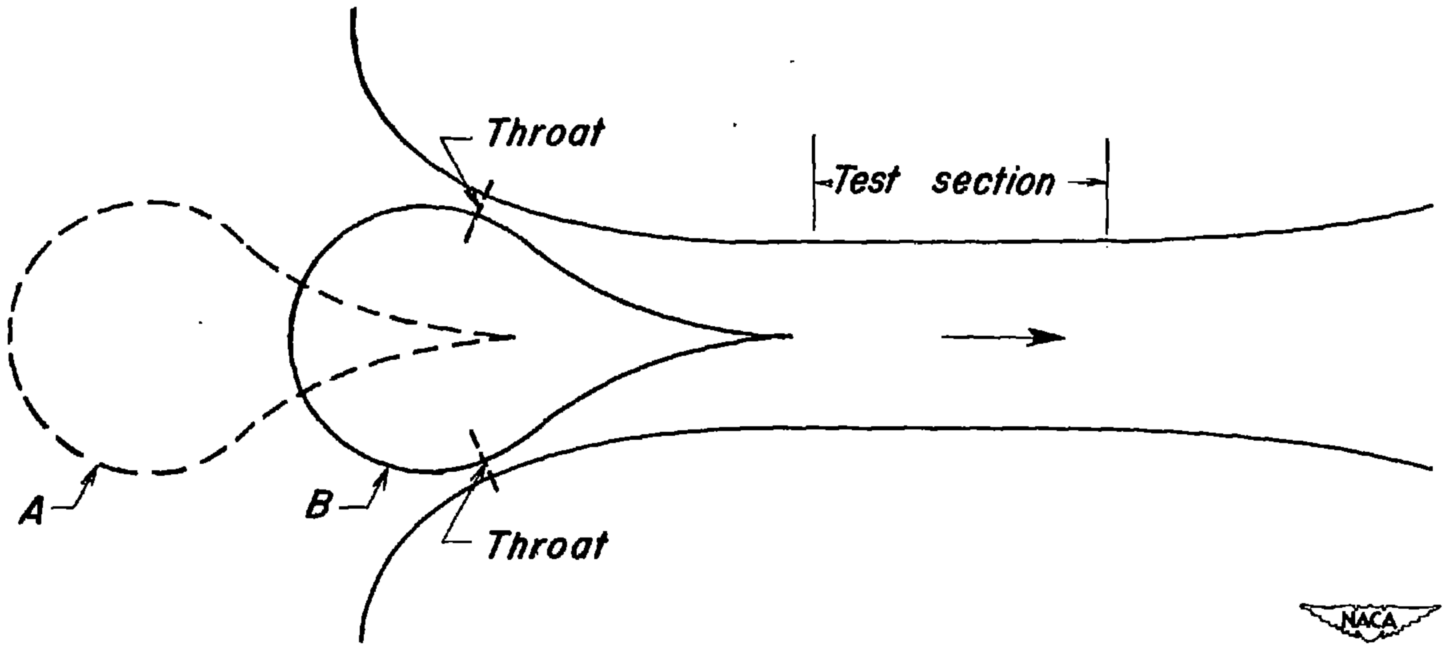

Figure 5.— Silverstein plug-type supersonic nozzle.

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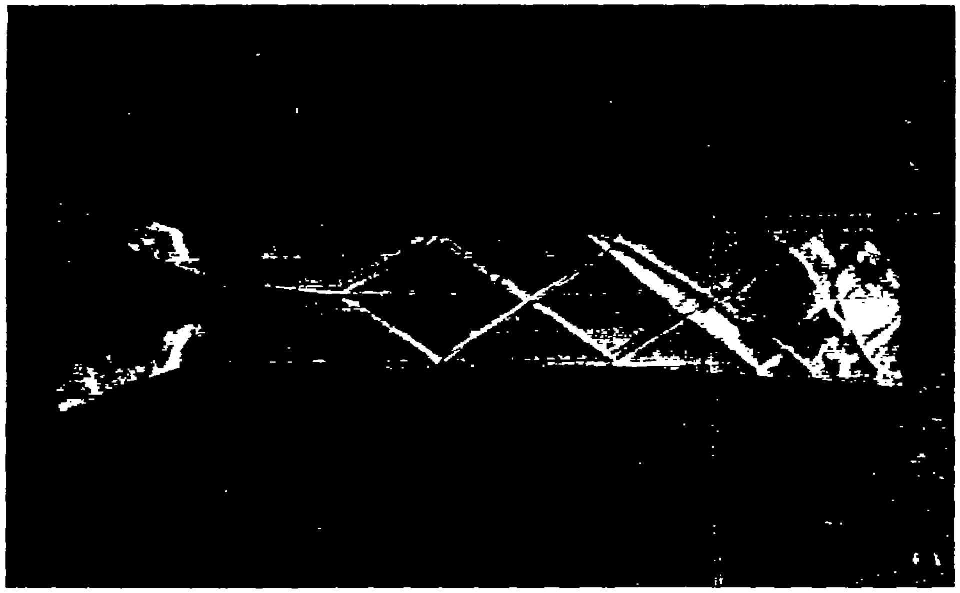
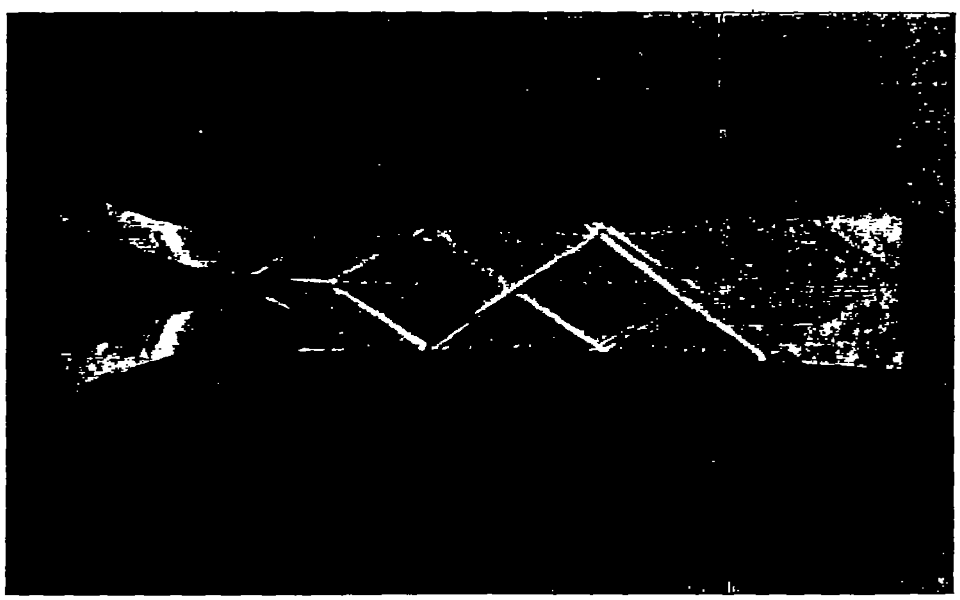


(a) Without boundary-layer control.



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(b) With boundary-layer control.
Figure 6.– Schlieren photograph of the flow through a two-dimensional plug-type nozzle.

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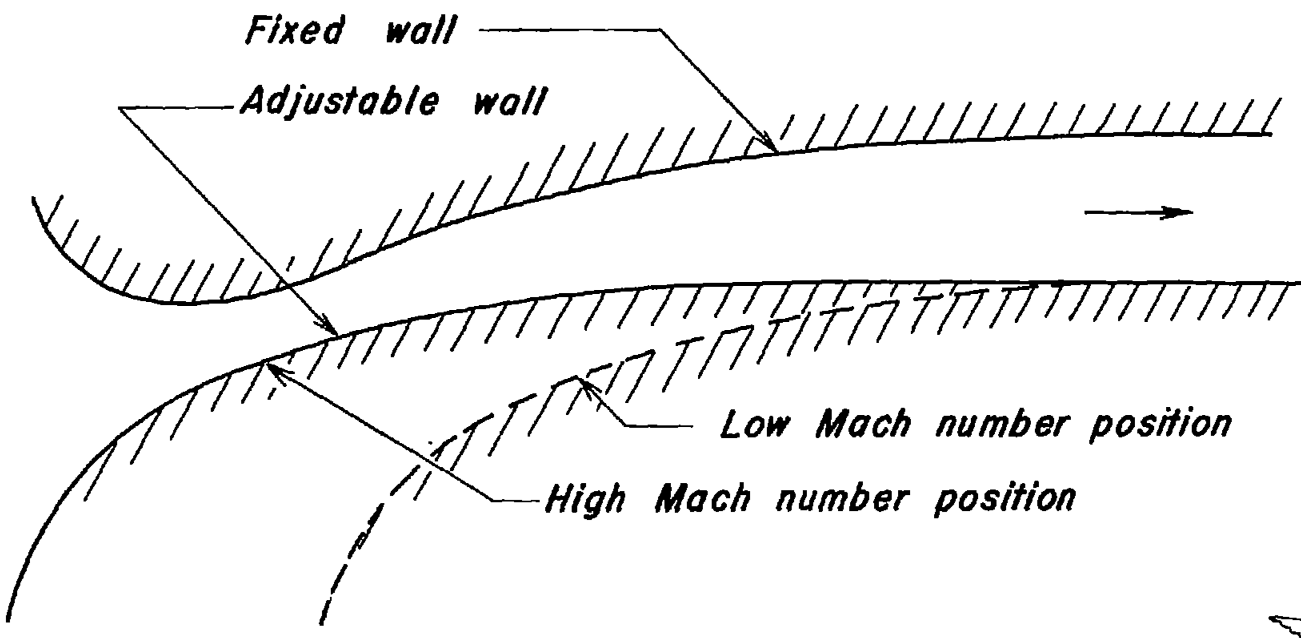

Figure 7.— Asymmetric adjustable supersonic nozzle.

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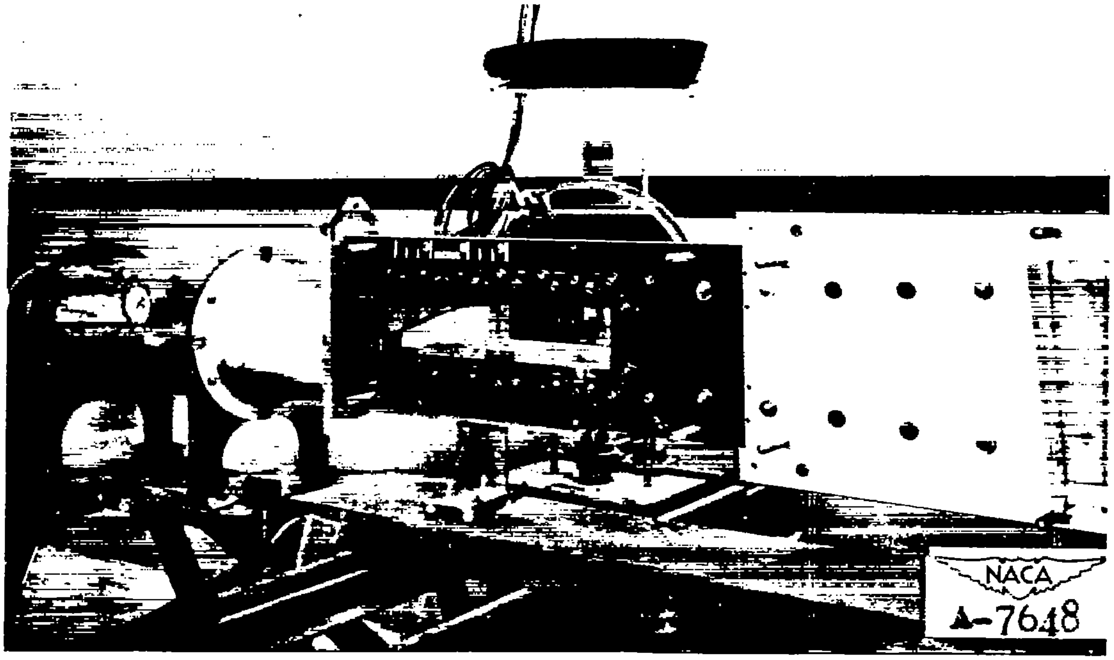
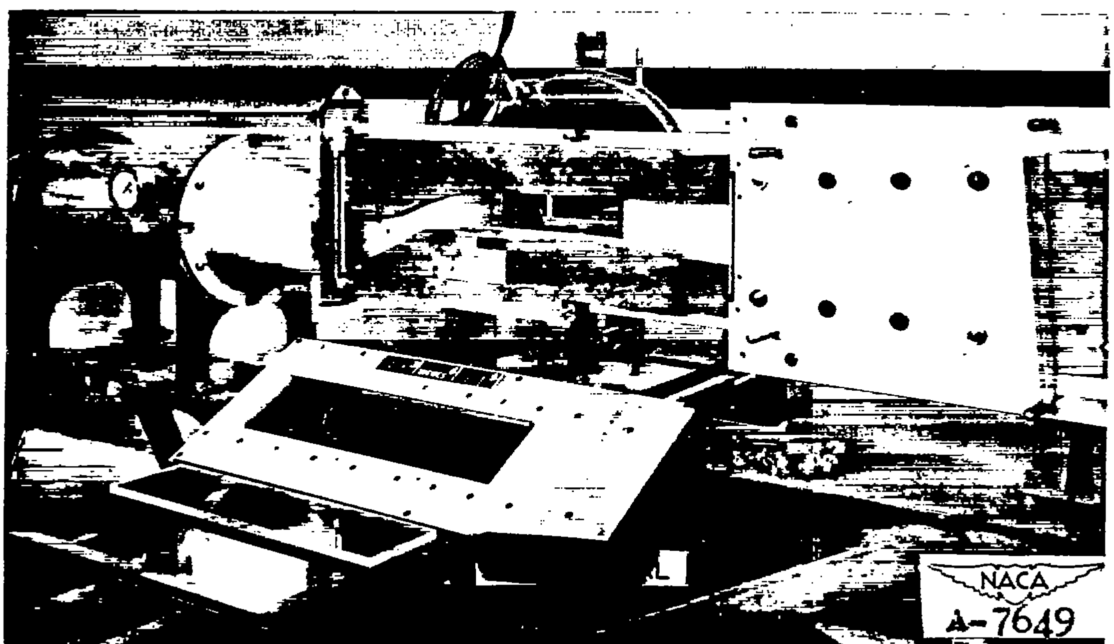


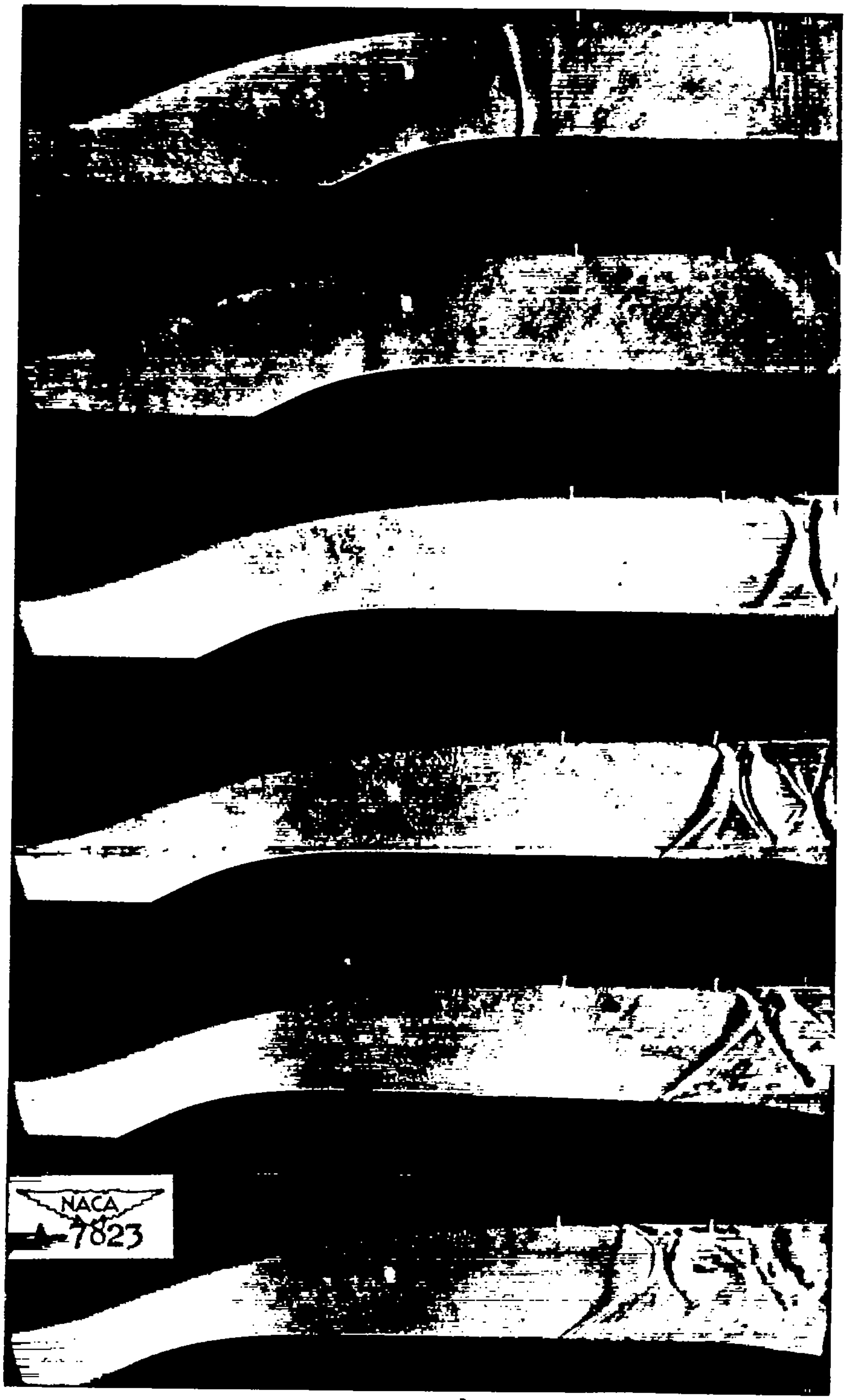
(a) Model nozzle assembled.



(b) Model nozzle with side plates and windows removed.
Figure 8.– The 1-1/2-by 1-1/2-inch asymmetric adjustable nozzle.

[redacted]

[redacted]



[redacted]

(a) Nearly satisfactory nozzle.
Figure 9.— Schlieren photographs of flow through an asymmetric adjustable supersonic nozzle at various Mach numbers.

[redacted]

[redacted]

$M \cong 1.13$

$M \cong 1.31$.

$M \cong 1.57$.

$M \cong 1.72$.

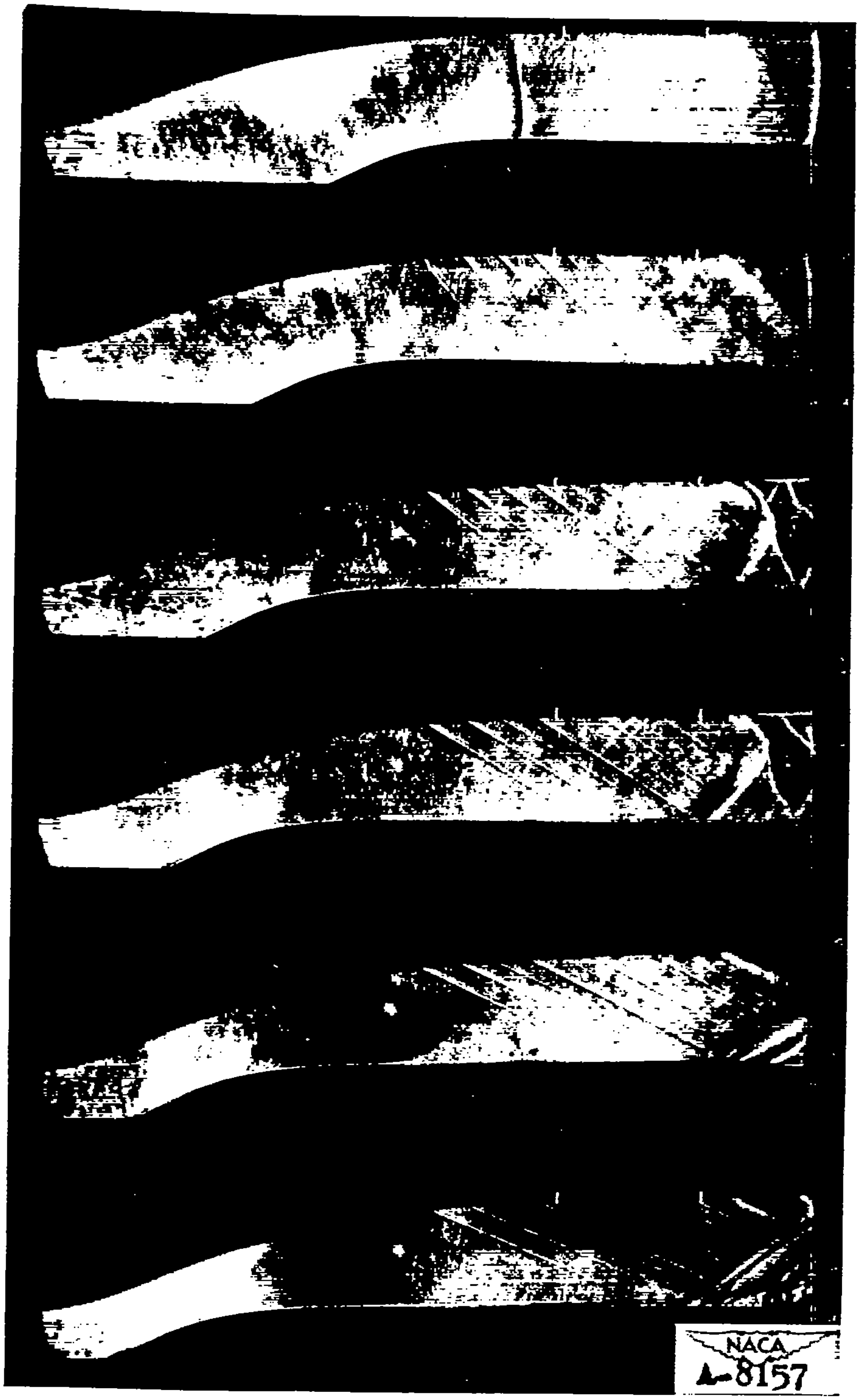
$M \cong 1.94$.

$M \cong 2.09$

Supersonic flow not established.

[redacted]

(b) Unsatisfactory nozzle.
Figure 9.— Continued.



Supersonic flow not established.

M $\cong$ 1.34.

M $\cong$ 1.54.

M $\cong$ 1.72.

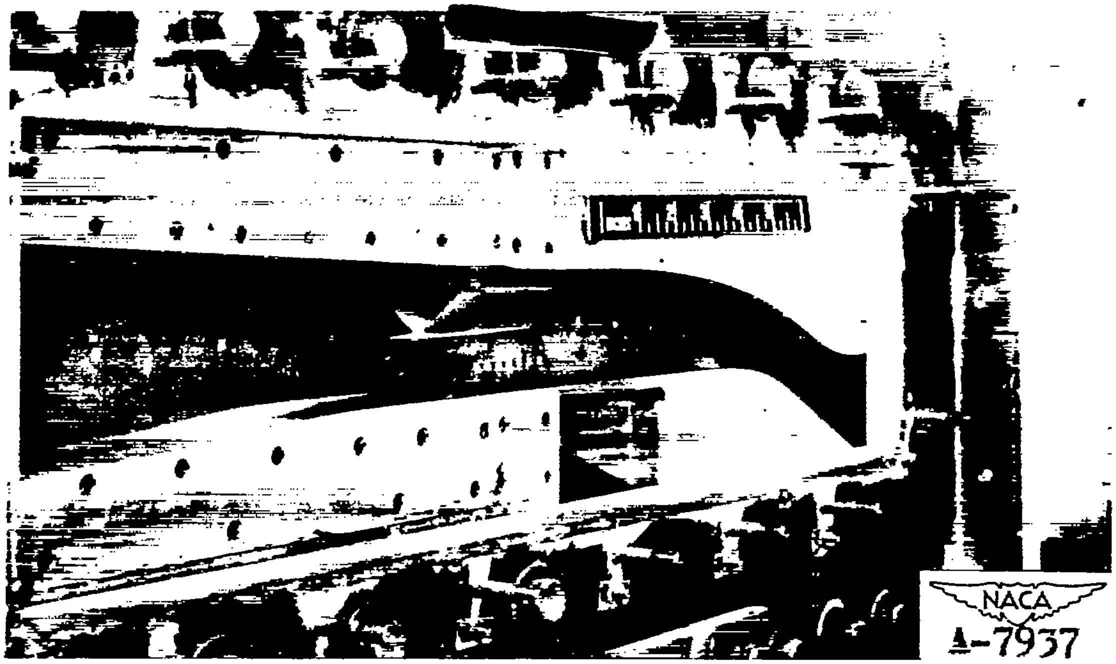
M $\cong$ 1.94.

M $\cong$ 2.21.

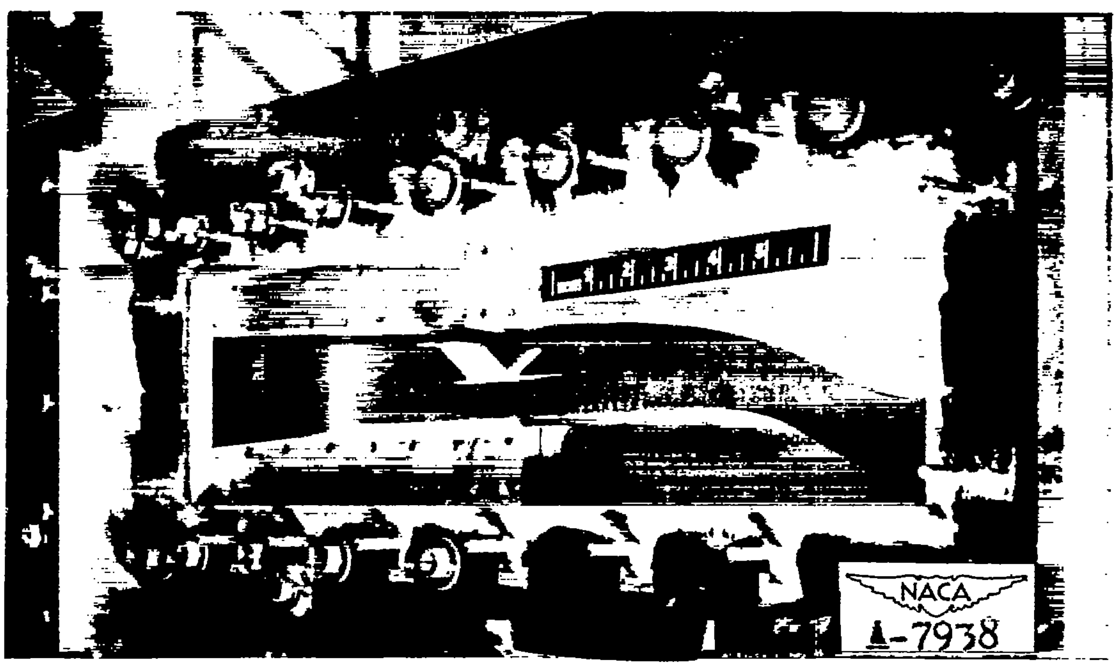
[redacted]

(c) Pictures taken with small indentations on concave wall.

Figure 9.— Concluded.



(a) Three-quarter rear view.



(b) Three-quarter front view.

Figure 10.– The 1-1/2- by 1-1/2-inch asymmetric adjustable nozzle with model support gear installed.

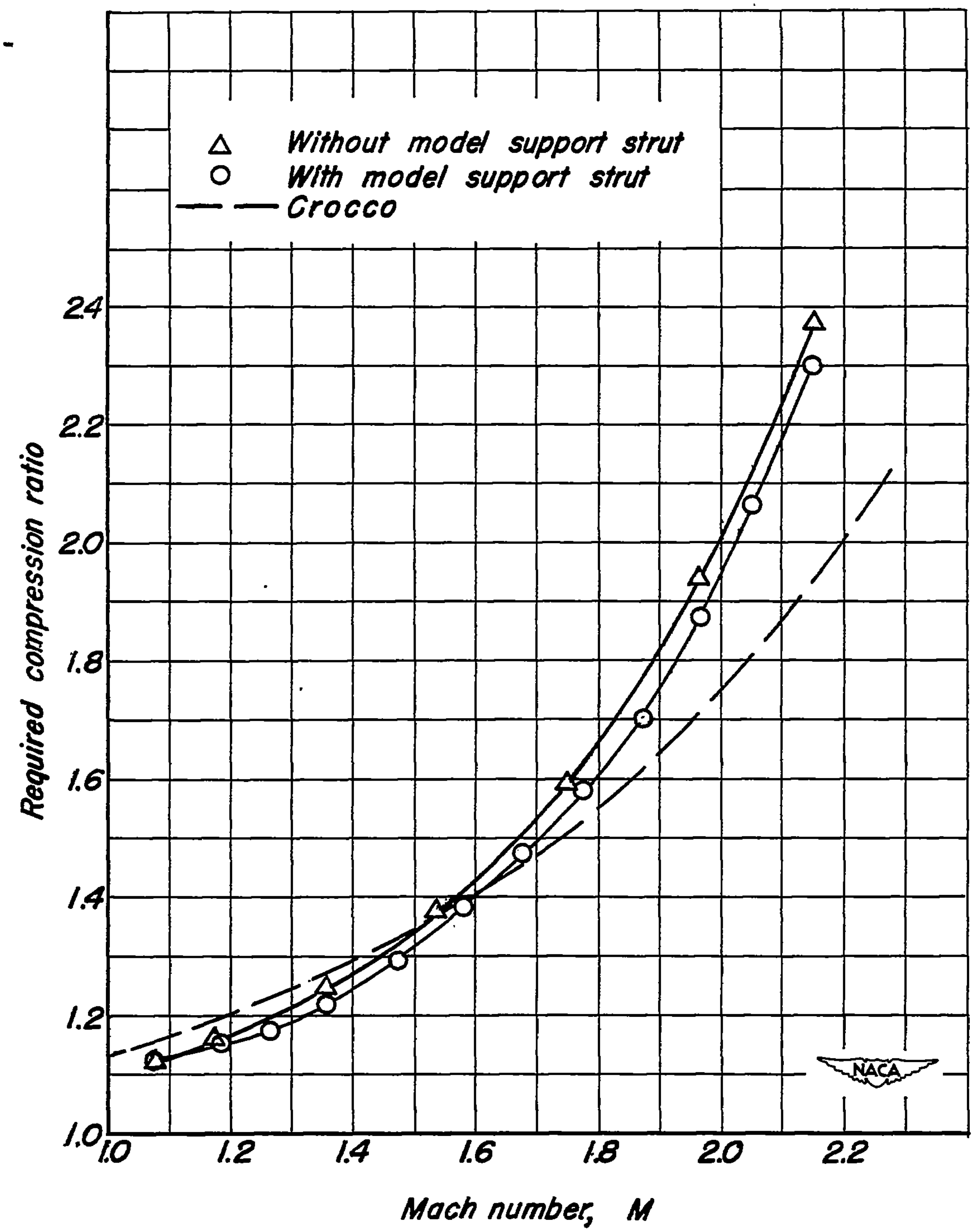
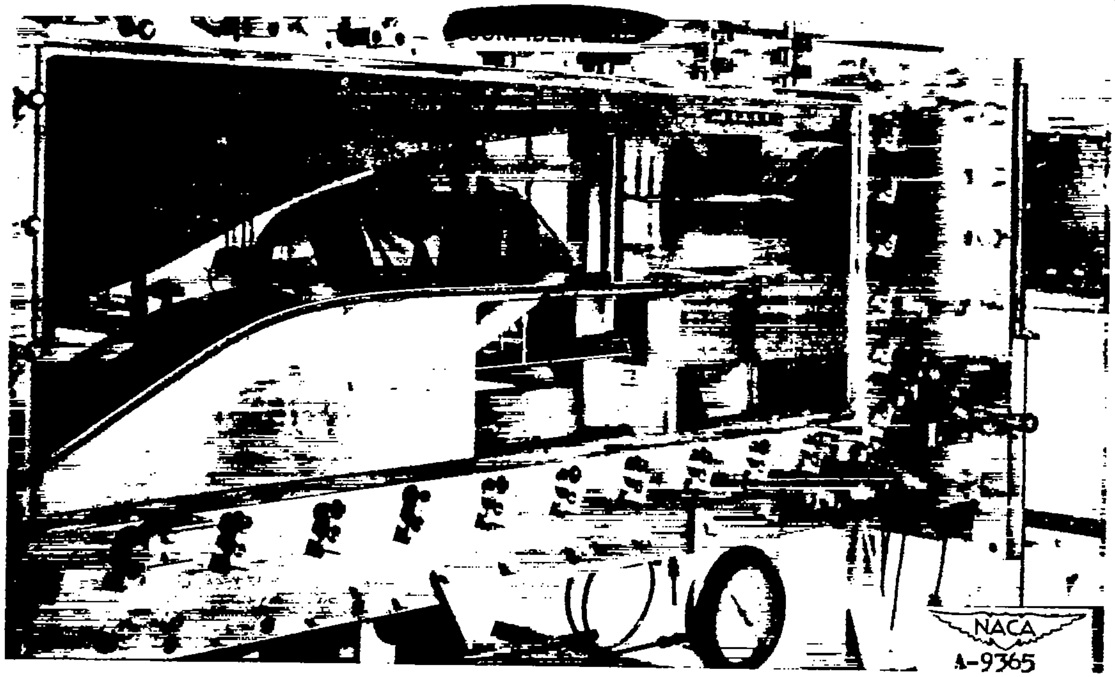


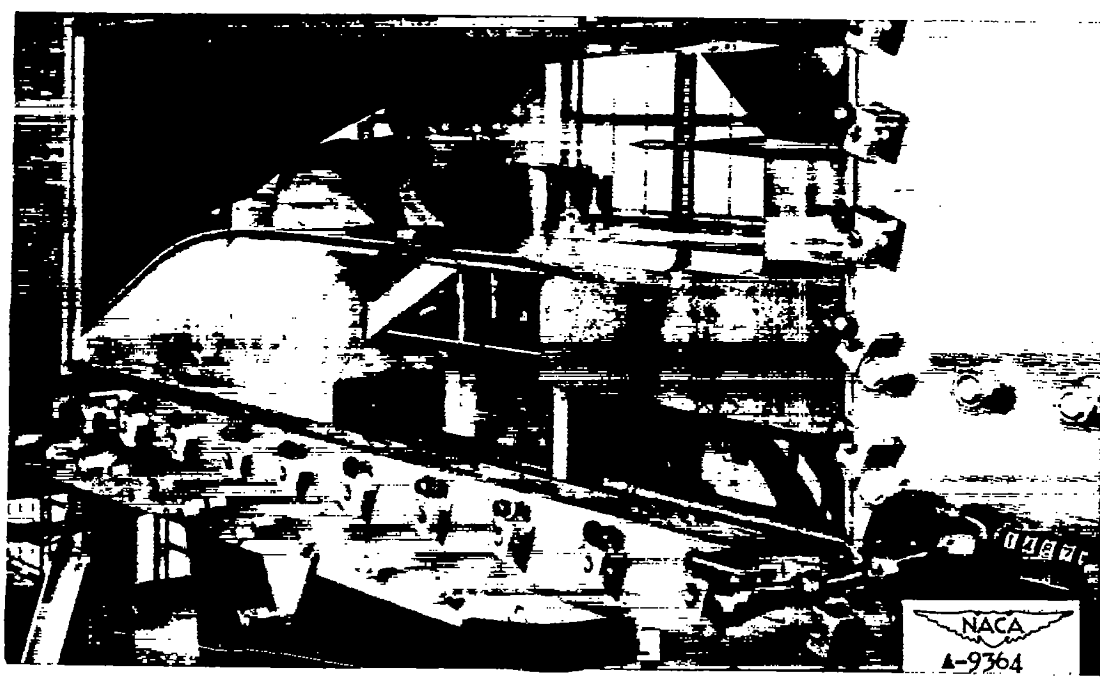
Figure 11.— Compression ratio required for $1\frac{1}{2}$- x $1\frac{1}{2}$-inch asymmetric adjustable nozzle (atmospheric exit).

[redacted]

[redacted]



(a) Three—quarter front view.



(b) Three—quarter rear view.
Figure 12.— The 8— by 8—inch wind tunnel with sidewalls removed.

[redacted]

[redacted]

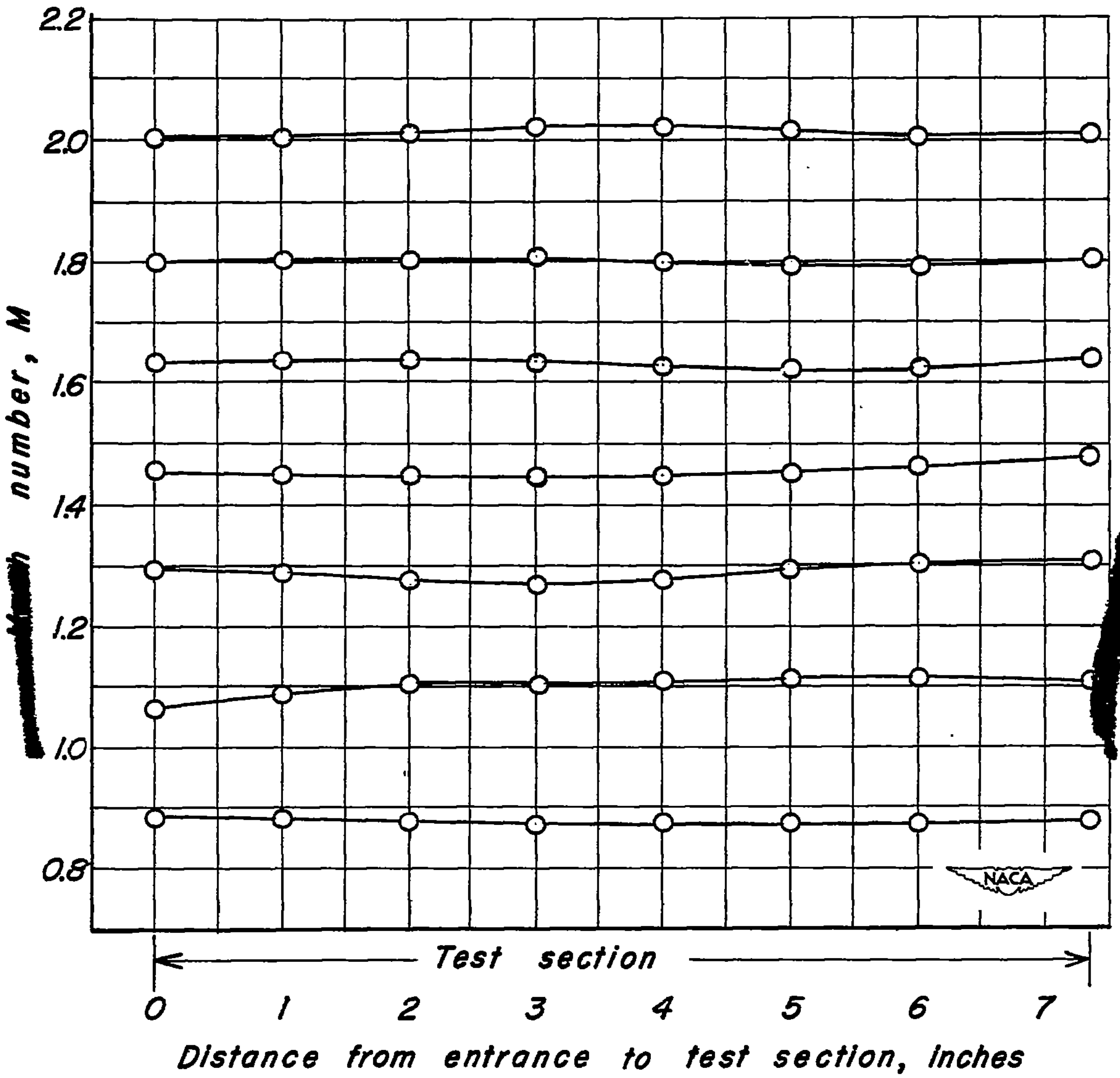


Figure 13.– Longitudinal Mach number distribution in 8-by 8-inch wind tunnel (from side-wall mid-height pressure measurements).

[redacted]

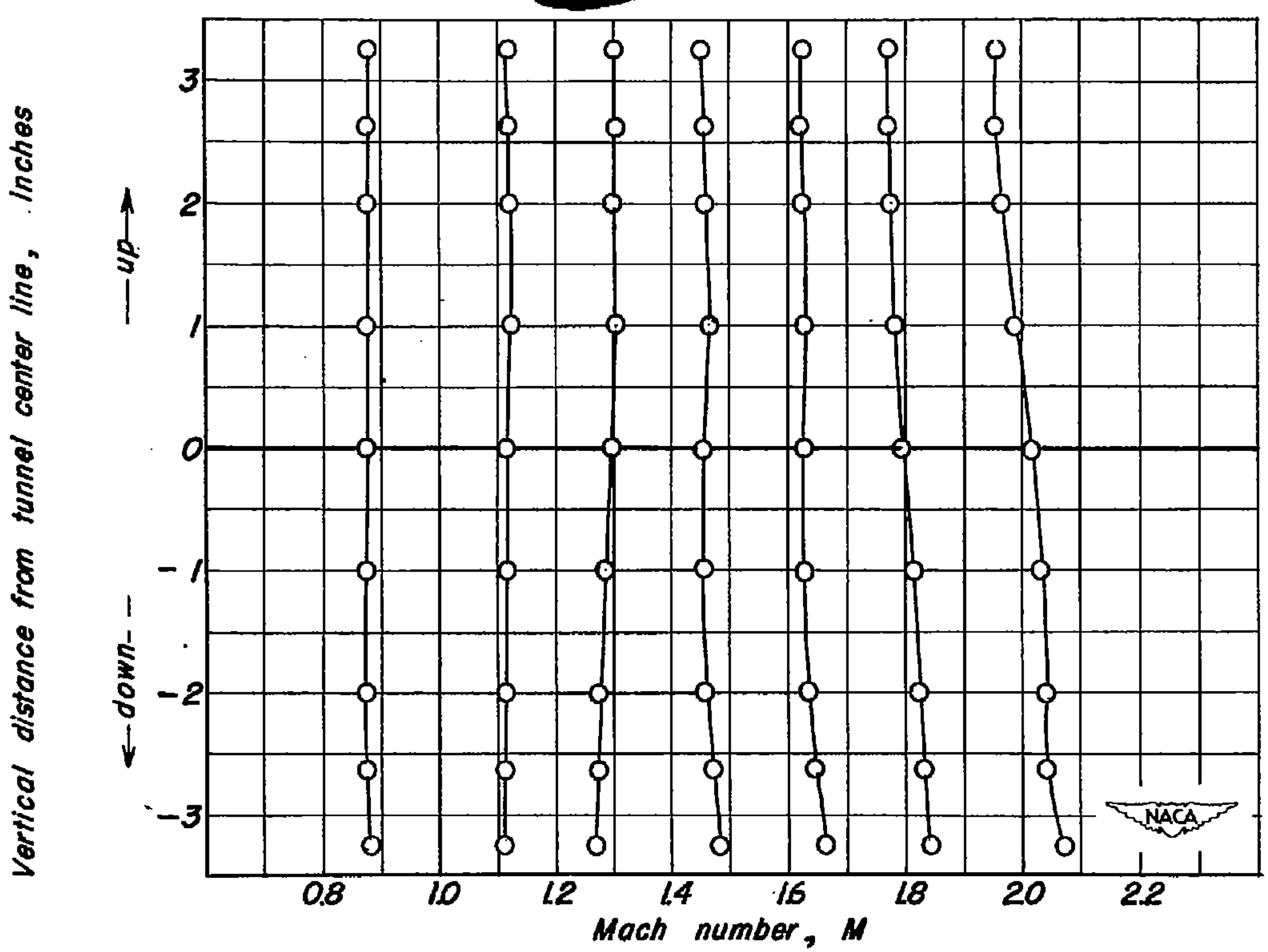


Figure 14.— Vertical Mach number distribution in 8- by 8-inch wind tunnel (from side-wall pressure measurements at station five inches downstream of entrance to test section).

[redacted]